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A PROGRAM FOR THE INVESTIGATION OF THE MULTIBODY MODELING, VERIFICATION, AND CONTROL LABORATORY

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ABSTRACT

The Multibody Modeling, Verification, and Control (MMVC) Laboratory is under development at the NASA Marshall Space Flight Center in Huntsville, Alabama. The laboratory will provide a facility in which dynamic tests and analyses of multibody flexible structures representative of future space systems can be conducted. The purpose of the tests are to acquire dynamic measurements of the flexible structures undergoing large angle motions and use the data to validate the multibody modeling code, TREETOPS, developed under sponsorship of NASA. Advanced control systems design and system identification methodologies will also be implemented in the MMVC laboratory.

This paper describes the ground test facility, the real-time control system, and the experiments. A top-level description of the TREETOPS code is also included along with the validation plan for the MMVC program. Dynamic test results from component testing are also presented and discussed. A detailed discussion of the test articles, which manifest the properties of large flexible space structures, is included along with a discussion of the various candidate control methodologies to be applied in the laboratory.

INTRODUCTION

Approximate numerical methods are generally employed to solve the nonlinear partial differential equations for flexible multibody dynamics. The TREETOPS multibody modeling code is one such tool. This code uses Kane's equations and the component mode approach for multibody simulation. To date, verification of multibody tools have has been limited to the fixed point case, accomplished by comparing component and system mode results to those of the NASTRAN finite element code. Validation of the modeled nonlinear behavior can not be accomplished in this manner. Hardware experiments highlighting modeling features of interest, such as large angle slewing, are required for such validation. The Multibody Modeling, Verification, and Control (MMVC) Program at Marshall Space Flight Center (MSFC) is focused on the experimental validation of multibody modeling codes and the application of control theory to nonlinear dynamic systems.

The MMVC Program was initiated in November, 1990. The MMVC laboratory is currently under development and will provide a testbed for the execution of experiments designed specifically to validate modeling of complex systems. Modeling features under study are body flexibility, including large motions with small and large deformation; interface degree-of-freedom, including point and line interfaces undergoing translation and rotation; geometric stiffness, including gravity and foreshortening; and constraints, including prescribed motions and closed-tree topologies. The top-level design of a basic set of experiments that emphasize critical modeling features presently included in the TREETOPS simulation has been completed. Beginning with a simple single beam experiment and evolving to multiple beams, joints, and various topologies, the experiments will grow in complexity as each modeling feature is examined. The final experiment will feature a test article traceable to the Advanced X-Ray Astronomical Facility (AXAF). Figure 1 depicts the general methodology of the MMVC validation plan. Experiment hardware has been fabricated, and individual components have been tested. Detailed procedures for system-level experiments are being developed.

Critical to the experiments is the design and development of a test facility. A facility design was chosen such that an existing platform will be modified to accommodate the MMVC experiments. Additional structure will be added to the platform to provide a support base for the test articles and to raise the fundamental frequency of the platform such that it is outside the frequency range of interest for the experiments. The facility design has been finalized, and fabrication should be completed next year. An integral part of the facility is the real-time closed-loop system (RTCS). Its function is to process the sensor inputs, implement the controller, and provide the real-time output signals to the actuators. The RTCS is in place and functionally verified.

As part of the MMVC program, enhancements to the TREETOPS code are planned. The goal is to develop a Government-owned "all-in-one" tool that can be used to develop structural models of multibody systems, perform model order reduction, develop controllers, and assess controller performance in a closed-loop sense via simulation. Currently, the simulation tool is a menu-driven program used to model and analyze flexible multibody structures exhibiting either open- or closed-tree topologies. The menu program provides the means to implement gains for a standard proportional, integral, differential (PID) controller or to include a user-defined controller. The results of this effort will be the enhancement of TREETOPS to include model reduction techniques, thermal effects, optical path analysis capability, expanded controller design capability, and to improve computational efficiency.

The MMVC Program at MSFC will provide experimental validation of multibody simulations and lead to the development of a Government-owned multibody modeling and control system design and analysis tool. The results of the experiments and the enhanced TREETOPS code are and will be publicly available upon request to the Government. The following

sections contain brief descriptions of the TREETOPS code and planned enhancements, the MMVC experiments and validation plan, the MMVC facility, and highlights of the control design techniques envisioned for use in the closed-loop control experiments.

DESCRIPTION OF THE TREETOPS MODELING TOOL

Introduction

TREETOPS is a time history simulation of the motion of arbitrary complex multibody flexible structures with active control elements.[1] The name TREETOPS, which is not an acronym, refers to the class of structures whose motion can be simulated by the program, those having an open- or a closed-tree topology. The program offers the user an advanced capability for analyzing the dynamics and control-related issues of such structures.

In the simulation, the total structure is considered as an interconnected set of individual bodies, each described by its own modal characteristics with prescribed boundary conditions. An interactive set-up program creates all necessary data files. A linearization option that provides both the simplified model typically used during the initial phases of control system design and the complex model needed for final verification is also available. Thus, TREETOPS can be used throughout the life of a project, and the user is not required to learn a new simulation system as the project progresses.

In addition to multibody simulation, TREETOPS contains subroutines for control system analysis and design. Using this complete capability, the user can create and linearize complex, multibody models, import the plant model into MATLAB, design a feedback compensator in matrix form and export the results back to TREETOPS as a 'matrix controller' for final design verification.

The current version can be configured to execute on most Unix platforms as well as PC class machines. The graphics program, TREEPLOT, is customized for specific monitors and printers and is continuously updated. The PC version of TREEPLOT has yet to be developed; however, TREETOPS is completely compatible with the PC version of MATLAB and this product can be used for obtaining graphical output from TREETOPS.

Planned Enhancements for TREETOPS

A number of enhancements are planned for TREETOPS. Among these enhancements are order-N formulation for greater computational efficiency, the inclusion of inverse dynamics control and geometric nonlinearities, and an improved graphical user interface (GUI).

The multibody dynamics formulation and corresponding solution algorithm presently employed in TREETOPS is classified as an order-N-cubed approach, where N is the number of degrees of freedom. The dynamic equations of motion are formulated using Kane's Equations. The algorithm currently in use involves a matrix-vector implementation wherein a generalized NxN system mass matrix is formed and inverted

to solve for the N degree of freedom accelerations. This procedure requires N^3 operations. Research in numerical analysis has demonstrated that such problems can be solved using order-N algorithms requiring N operations. These algorithms essentially perform recursive operations to solve the equations of motion wherein the assembly and inversion of a system mass matrix is avoided. For a large system order, order-N techniques result in a substantial savings in computational time.

The increasing demand for high-operating speed, accuracy, and efficiency has led to strict requirements on the design of control systems for space-based manipulators. This requires consideration of a set of highly coupled nonlinear dynamic equations to determine the control torques and forces necessary to produce the desired motion of the manipulator. This also suggests the use of more sophisticated control schemes, such as inverse dynamics controllers. Hence, this feature will be added to TREETOPS. This enhancement is discussed in more detail in a later section.

Another planned enhancement is the inclusion of the effects of geometric nonlinearities. When properly accounted for, these terms will accurately reflect the motion induced change in stiffness of the structure. The current version of TREETOPS uses the assumed modes method to describe the elasticity in the links. The assumption in this method is that the elastic deflection is small and can be obtained as a linear superposition of the modes multiplied by their respective time-dependent amplitudes. These deflections are the axial and transverse elastic displacements, and rotations of a configuration point.

The assumed modes method is perhaps the most suitable method to describe the elasticity in any arbitrarily shaped body. Such a body can be mathematically discretized and its modal frequencies and mode shapes easily obtained using any linear finite element program. An approach is sought to compensate for the change in stiffness created by the use of the linear finite element program. One solution is the retention of the nonlinear part of the strain expression that is omitted in the linear finite element theory.

In the expression for the potential energy due to the nonlinear expression in the strain, the impressed loads (stresses) explicitly appear. Once these loads are specified, a stiffness matrix, called "the geometric stiffness matrix," which is analogous to the linear stiffness matrix, is obtained. This approach will be extended to multibody systems with arbitrarily shaped flexible bodies and included in the analysis code.

A GUI is currently under development. The goals for the GUI development are to increase learning speed and simulation implementation time, reduce errors, and encourage rapid recall for infrequent users. The desktop metaphor, with its windows, icons, and pull down menus, is very popular because it is easy to learn and requires minimal typing skills. The requirement to memorize arcane keyboard commands is also alleviated. The GUI will comprise full screen form using cursor keys and a mouse for movement from field to field. The input options will be designed as a set of icons.

TREETOPS currently lacks a unified environment in which to run the constituent programs with transparent data communications. The user must invoke each program at the command line with a problem name. The commands have a three level hierarchy. The user is constrained to sequential movement from a higher level to lower level. In addition the user must remember the exact command for each operation. Thus the user has the burden of with committing the entire command set to memory. With the new GUI, the user will be able to specify a problem name and choose any of the available options, including NASTRAN, TREESET, TREESEL, MATLAB, and others. If the option the user selects requires any interaction, then a form for that interaction is presented on the screen and the users simply provides the required input data. Communication between the different program elements will be through data files, but will be transparent to the user. The GUI will also have an extensive error checking routine executed at all stages of data entry. When an error is detected, the GUI will prompt the user to re-enter the data.

TREETOPS Modeling Features to be Verified via Laboratory Experiments

Several aspects of the flexible multibody modeling problem will be examined in the MMVC program. The primary focus will be on the evaluation of the assumed modes method when applied to multibody systems. In this technique, the structural flexibility of each body is modeled as a linear combination of spatial shape functions and generalized time coordinates. Through proper selection of the component shape functions or Ritz vectors, the system dynamic characteristics may be recovered. Several points will be addressed concerning the selection of the Ritz vectors. First, the type of Ritz vectors that should be used for various classes of multibody systems will be assessed. These vectors may be normal modes, Lanczos modes, block Krylov modes, and shape functions from substructure coupling techniques. Next, the sets of shape functions to be retained for each body will be determined as will the boundary conditions to be used in computing these shape functions. These points will be addressed through a series of increasingly complex experiments to be conducted in the MMVC laboratory. The experiments will be designed such that the flexible effects of the components dominate the time response of the system.

Experiments will also be designed to examine other aspects of multibody systems. Modeling techniques will be evaluated which account for geometric stiffening of systems described through the assumed modes method. These techniques account for changes in structural stiffness induced by motion and gravity. In particular, experiments will be performed to measure the time response of systems undergoing buckling loads and large angular velocities. These results will be compared to analytical predictions which account for the changes in stiffness. Additional studies will be performed to evaluate modeling techniques in the areas of joint friction, joint flexibility, kinematic and closed-loop constraints.

Assumed Modes Validation Plan

The MMVC validation plan consists of verification of the assumed modes hypothesis for a multibody structure and

will provide insight as to how the multibody structures should be modeled. The current procedure consists of three steps; 1) model development, 2) data collection, 3) post test analysis. The overall plan is illustrated in Figures 2, 3, and 4.

MMVC EXPERIMENTS

The proposed series of experiments for the MMVC program can be classified into three categories: 1) Open-loop topologies, 2) Closed-loop topologies, and 3) Space structures. Each of these categories have specific issues associated with them. For example, the open-loop topologies have one actuator for each joint while the closed topologies have fewer actuators than joints. Furthermore, in closed-loop topologies the component flexible links can be modeled independently, but the system imposes interdependencies between the component modes through closed-loop constraints. Space structures can belong to any of the above categories but elaborate modeling may be required and the control objectives may also differ significantly from those in the first two categories.

A set of experiments has been devised to address the modeling issues identified in the MMVC program. The first group of experiments considers open-loop topologies, the second set is for closed-loops, and the last set focuses on a representative space structure. The experiments are previewed in the following sections and the specific issues of each experiment are addressed. The experiments are ordered according to complexity. Each configuration will be used to address several modeling and dynamics issues and incorporate several control objectives.

Two control objectives will be used in virtually all configurations; pick-and-place control and trajectory control. The objective of pick-and-place is to move from one point to another without regard to the trajectory, while the second approach specifies the trajectory to be followed.

Open-Loop Topologies

The experiments designed for this class of problems are composed of single and two link systems connected through active and passive joints to a moving base. The base may be held fixed or actively controlled. The experiment configurations are based on a building block approach using interchangeable components. The designer may select from a wide variety of links with varying dynamic characteristics. There are aluminum and steel beams of varying cross sections and lengths, as well as more complex "geodesic" and "ladder" beams. Each of the beams has been modeled in NASTRAN and its component characteristics documented. There are standard mechanical interfaces to attach the beams to passive and active joints as well as tip masses and counter weights. The active joints are driven by DC torque motors and may be configured for planer or three dimensional experiments. Figures 5, 6, 7, and 8 are typical open-loop topology experiments. The objectives of the open-loop experiments are:

1) To demonstrate the coupling between rigid body and elastic motion of systems.
2) To address the issue of modal selection and types of shape functions used in the modeling process.

3) To investigate motion induced stiffness changes.

The control objectives are:

1) Pick and place control.
2) Pointing control.
3) Pendulum mode control.

Closed-Loop Topologies

This class of experiments consists of combinations of rigid and flexible links forming a closed-loop mechanism as shown in Figure 9. Typically, the number of active joints in the system is greater than the number of passive joints. These experiments are designed to validate use of kinematic and closed-loop constraints equations in multibody codes.

Space Structures

The previous beam experiments were designed to address several aspects of multibody dynamics and control through increasing levels of complexity. The Very Elastic Rotating NASA Experiment (VERNE) will incorporate the experience gained thus far into the modeling and control of a complex spacecraft. VERNE, shown in Figure 10, is composed of a moderately flexible core body, flexible pointing unit, two flexible solar arrays, and a pair of whip antennas with end masses. A rigid beam attaches the core body to the linear motion system of the facility through a ball joint. The experiment will inherently have two pendulum modes, which are rotations about the X and Y axes, and a roll mode about the Z axis. VERNE was designed such that the bending modes of the solar arrays and antenna are highly coupled with the pendulum modes. The pointing unit is connected to the core body through three linear electromechanical actuators, forming a closed-loop topology. The pointing unit has a range of motion of ± 30 degrees about the local X and Y axes. The linear actuators can generate a peak force of 200 pounds and have a throw of 18 inches. The pointing resolution of the unit computed from the accuracy of the incremental encoders on the lead screws of the actuators is .002 degrees. The point unit is two feet tall and is composed of three triangular plates connected by longerons. A generic housing was fabricated with the triangular plates to hold assorted laser or optical sensors.

The flexible solar panels are 8 feet long and 1 foot wide. The panels consist of thin aluminum struts bolted in a truss like fashion. The solar panels have 360 degrees of travel about the X axis and are powered by a direct drive D.C. motor. The drive shafts are instrumented with incremental encoders and tachometers. The encoder resolution is .35 degrees. The peak torque available from the motors is 11 foot-pounds.

The core body is composed of aluminum angle. The whip antenna are rigidly connected to the core body. Three orthogonal reaction wheels are mounted to the core body along the body axes. Each reaction wheel is driven by a D.C. torque motor equipped with a tachometer. The core body is also instrumented with a three axis rate gyro system.

The preliminary system modal characteristics are shown in Table 1. The first two bending modes at .263 and .275 Hertz are torsion modes of the solar panels about the drive shafts. The next mode is a

system pendulum mode at .366 Hertz about the Y axis. The bending mode at .484 Hertz is a combination pendulum mode about X and solar panel torsion. These modes may be shifted through the use of counter weights and adjustments to the solar panels and antenna.

Table 1. Preliminary System Modal Characteristics

Mode	Frequency (Hz)	Description
1	0	Rigid Body Rotation About Z
2	.263	Solar Panel Rotation in Phase
3	.275	Solar Panel Rotation
4	.366	Pendulum About Y
5	.484	Pendulum About X / Solar Panel Torsion
6	1.577	Antenna 1st Bending About X in Phase
7	1.640	Antenna 1st Bending About X
8	1.718	Antenna 1st Bending About Z
9	1.795	Antenna 1st Bending About Z
10	5.164	Solar Panel 1st Bending

VERNE Experiments

The objectives of the experiments proposed for VERNE are divided into dynamics and controls. The objectives of the dynamic open-loop tests are:

1) to test the validity of the generalization of modal selection issues from earlier experiments.
2) to study the pendulum modes in a multi-body context.
3) to study motion coupling through various prescribed open-loop maneuvers.

The control objectives are:

1) pointing control in the presence of base excitation.
2) pointing control in the presence of solar panel maneuvers.
3) pointing control in the presence of pendulum modes.

Three open-loop experiments have been proposed. First, the translational degree of freedom of the linear motion system will be locked and the solar panels will be driven through various slew maneuvers. Next, the solar panels will be held fixed and the system will be driven through base excitation. Finally, the solar panels will again be driven, but this time in the presence of base excitation. The effect of solar array motion and base excitation on the system pendulum modes will be studied using sensor time histories and compared to analytical results.

The controls experiments consist of accurately pointing the lower unit in the presence of solar panel motion and base excitation. The control system designer will

have access to line of sight error from a light source on the lower unit illuminating a quad detector on the ground. The designer will also have information from the rate gyros, solar panel drive shaft position and rate, and relative angle between the core body and lower pointing unit. The engineer must design the loops generating torque/force commands for the reaction wheels, solar panel drives, and linear actuators from the feedback of the various sensors.

THE MMVC LABORATORY FACILITY

The MMVC project consist of multibody modeling, verification, and control. Currently dynamic multibody systems with flexible members and large rotations and translations at the joints are modeled using TREETOPS. Information on the flexible modes is input to the code from NASTRAN models of the bodies. There are many open questions as to which modes should be input to TREETOPS - that will be addressed in the modeling experiments. TREETOPS has been widely used for many years, but its results have never been experimentally confirmed. This issue will be addressed in the verification section. Finally, new methods for control of the structures will be investigated in the control section.

Platform and Linear Motion System Design

The MMVC facility will be located in the west high bay area of building 4619 at MSFC. This facility is joined with the Flexible Space Structures (FSS) ground test facilities and is accessed via the control room. The two primary requirements for MMVC facility are experiment work volume and support structure stiffness. The desired work volume is 20' by 20' by 20'. This will allow room for large translations and rotations of the experiments, as well as for larger test articles needed for low frequency modes. The experiment support structure must withstand the static and dynamic loads from the test articles. The structure should also isolate the experiments from unwanted disturbances. Isolation will be accomplished by moving the support structure natural frequencies to a range outside of those under study. Other factors considered in designing the facility were: facility enclosure, power, lighting, ventilation, access, safety, and cost.

Currently, outside of the FSS control room in Building 4619, there is a balcony off the third floor in the high bay. Three locations for the facility were considered. First, the experiments could be hung from the existing balcony. Second, the experiments could be enclosed in a stand-alone structure below the existing balcony on the first floor. Finally, the test articles could be suspended from a fixture above the existing balcony. The last alternative was chosen because of several advantages. The primary advantage is that the real-time computer controlling the experiments will be located in the existing FSS control room. Also, test articles will be highly visible from the control room and the current platform or balcony. This location will have a high work volume and require no external lighting or ventilation. The system bending modes computed from finite element analysis are shown in Table 2. These modes were calculated assuming an 800 pound experiment located in the center of the front edge of the new platform. As expected, this is a diving board mode of the new structure at 19.7 Hertz. The frequency is well above those of interest of the experiments.

Table 2. MMVC Facility

Mode	Frequency	Description
1	19.702 Hz	Platform Bending
2	22.381 Hz	Localized Torsion
3	23.540 Hz	Localized Bending
4	25.550 Hz	Localized Torsion
5	27.872 Hz	Localized Bending

A linear motion system will be installed along the front edge of the new balcony. The motion system has a range of travel of 6 feet with a sensor resolution of .003 inches. It is a ball screw system driven by a brushless DC motor with a peak force capability of 430 pounds and can withstand loads well above 800 pounds.

MMVC Real-Time Control System

The user interface is through the Silicon Graphics Personal Iris 4D-25TG console. The real-time functions will be predominantly executed on four Mercury Computer Systems MC860VB-4 single board computers running MC/OS Version 2.0. A SPARC Engine 1E single board computer serves as a host for the MC860VBs. The host interfaces the Mercury boards to a SCSI bus and Ethernet.

The I/O boards consist of a Xycom XVME-203 Counter/Timer Board, a VME Microsystems International VMIVME-2528 128-bit Digital I/O Board, four Datel DVME-611F 14-bit Analog Input Boards, and four VME Microsystems International VMIVME-4100 Analog Output Boards. The MMVC Closed-Loop Controller will be used to provide digital control of the test articles in the MMVC Lab. The controller will be interfaced to the experiment of sensors, compute control outputs, and apply the outputs to the experiment of actuators. The closed-loop control laws will require a large amount of computational power, and must be executed at rates as high as 250 Hz.

MMVC CONTROLLER METHODS

Many control schemes have been evaluated that would not only provide adequate tracking, but also provide vibration suppression. The major problem with these linear design techniques is that the structure (plant) is a highly nonlinear system. Control design studies have showed that a linear controller, designed for the MMVC experiments may result in unstable systems for large-angle slew commands. This is because of the interactions between the control system and the nonlinear centrifugal stiffening, softening, and Coriolis effects. In the following paragraphs are presented three control schemes that may provide acceptable controllability and performance while the system is undergoing these nonlinear interactions.

Inverse Dynamics Controller

One approach to compensate for nonlinear forces is to use a technique referred to as inverse dynamics control.[2] [3] The way the inverse dynamics control law works is illustrated by considering the following equation

$$m(q)\ddot{q} \quad u(q,\dot{q}) = B(q)r \qquad (1)$$

where q is the n-dimensional vector of generalized coordinates, M(q) is the n x n mass matrix, u is the n-dimensional vector including the effect of centripetal, Coriolis, and gravity terms as well as all other stiffness and damping terms, r is the external torque (or force) vector of dimension m, and B(q) is the n x m torque distribution matrix.

The idea of inverse dynamics control is to seek a nonlinear control logic expression

$$r = f(q, \dot{q}) \tag{2}$$

which, when substituted into equation (1), results in a linear closed-loop system. Here, we assume that the state vector, q, is available.

In this paper, we consider the general case where the number of external torques can be less than the number of the generalized coordinates describing the equation of motion (1). Several control logic expressions and their computational steps are developed to apply the inverse dynamics control to this case.

TREETOPS subroutine facilities are used to perform this computation. The state vector, q, is defined to be the set of the hinge angles and translations and the modal coordinates of flex modes. The non-actuator forces, i.e., forces due to gravity, stiffness, damping, etc. are summed with the inertial forces. Also, the torque distribution matrix B(q) is not directly computed.

Model Reference Adaptive Control

Another control design option for the MMVC experiments is a spin-off from the model reference adaptive control (MRAC) methodology referred to as Direct Multivariable Model Reference Adaptive Control (DMMRAC). The primary advantage DMMRAC possesses over conventional MRAC and other control techniques is that it is completely model independent. DMMRAC is a nonlinear adaptive control methodology driven only by the accumulated error between the reference model and plant outputs. The nonlinear part of the filter results from the adapting law being a function of the square of the reference model states. Unlike classical MRAC, DMMRAC does not require any knowledge of the plant. Therefore, the order of the reference model is strictly up to the designer. Conventional MRAC methods require the order of a reference model to be at least equal to that of the plant. This is a major drawback for these other methods because predicting the order of a complex nonlinear plant is essentially impossible.

Fuzzy Control

The MMVC team is currently searching for new and innovative control methods for large space structures. Fuzzy logic control holds much promise in this application.[4] [5] [6] Fuzzy logic is a rule-based control methodology based on linguistic phrases and provides control the way a human operator would. It is especially suited for the nonlinear, time varying, and ill-defined systems such as large flexible structures. Another key feature to fuzzy logic is that it is completely model independent. Typical fuzzy rules are of the form:

If X_1 is $A_{i,1}$ and X_2 is $A_{i,2}$
then U is B_i (3)

where X_1 and X_2 are the inputs to the controller, U is the output, A's and B's are membership functions, and the subscript i denotes the rule number. For example, a rule for line-of-sight error control may state "If the Line Of Sight (LOS) error is negative small and the change in the LOS error is positive big, then torque is positive small". Given input values of X_1 and X_2, the DOF of rule "i" is given by the minimum of the degrees of satisfaction of the individual antecedent clauses i.e.,

$$DOF = \min \{A_{i,1}(X_1), A_{i,2}(X_2), \ldots\} \quad (4)$$

The output value is computed by

$$u = \frac{\sum_{i=1}^{N} (DOF_i) B_i^d}{\sum_{i=1}^{N} (DOF_i)} \quad (5)$$

where B_i^d is called the defuzzified value of the membership function B_i and n is the number of rules. The defuzzified value of a membership function is the single value that best represents the controls linguistic description. If a rule is active for the present conditions such that its output is "increased moderately", the defuzzified value is the centroidal value about the abscissa. In this case the defuzzified value is 3.0.

For control of highly nonlinear, time varying, and hard-to-define dynamics of large flexible structures, fuzzy logic with its model independence properties may prove to be a very practical method of control.

CURRENT EXPERIMENT ACTIVITIES

In order to develop analytical models of the system configurations, it is essential to accurately model all of the components that comprise the system. Figures 2 and 4 conceptually describe this process. In order to increase the fidelity of the system components, the first phase of experimentation involves component testing. Component testing involves beam-element modal tests, joint-element dynamic and static testing, and frequency response testing of the sensors and actuators.

Free-free modal tests were performed on the beam specimens in order to validate component mode shapes and frequencies predicted by NASTRAN, and to identify the damping ratio of each component mode. As expected, the free-free NASTRAN predictions match well with the free-free test results, within about five percent. Table 3 shows the results of the free-free modal test for one particular beam.

The next phase in the component testing plan is clamped-free modal tests. These tests will attempt to validate the clamped-free modes predicted by NASTRAN. The clamped-free and free-free component modes can then be used in assembling models. Next, system-level experiments will be performed. At this point, modal analysis will be carried out to determine which type of modes to use and what type of substructure coupling method best predicts the results.

Table 3. Free-Free Modal Test Results: First Four Modes of DYN30-254

Mode	Frequency (Hz)	Damping (%)
First Bending	3.24	3.5
Second Bending	8.59	1.4
Third Bending	17.23	0.9
Fourth Bending	30.67	0.5

SUMMARY

The MMVC program has been established at MSFC to experimentally validate multibody modeling codes and to improve the computational efficiency of such codes. Experiments have been designed to emphasize modeling features that are to be verified and validated in the effort. A laboratory facility has been designed and is under development. The RTCS is in place and has been functionally verified. Preliminary experiments that do not require the test volume to be provided when construction of the MMVC laboratory is completed are under way. Enhancements to the TREETOPS code are initiated and ongoing. This paper has presented a top-level overview of the MMVC program and its goals and methods.

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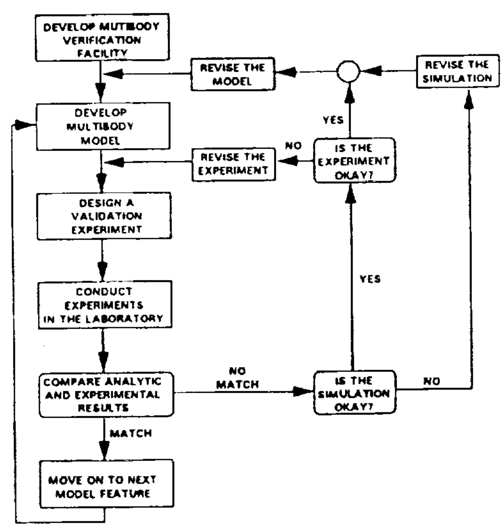

Figure 1

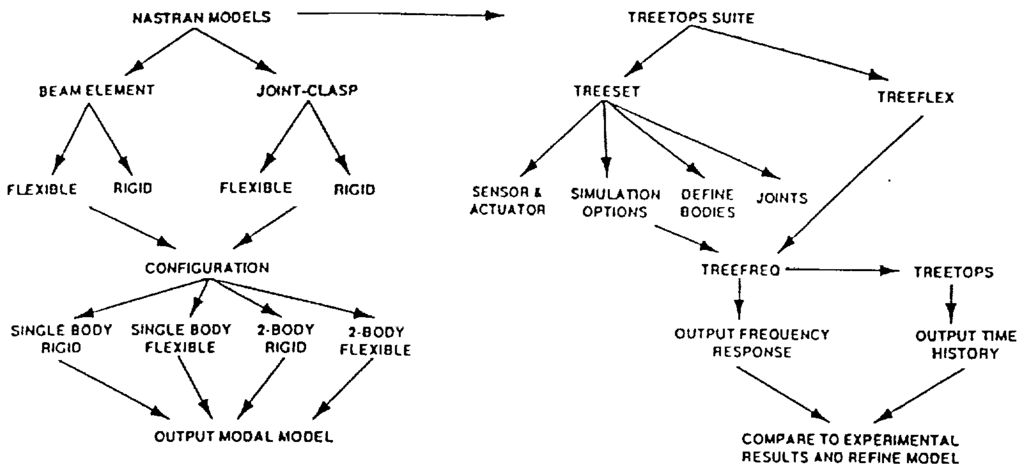

Figure 2

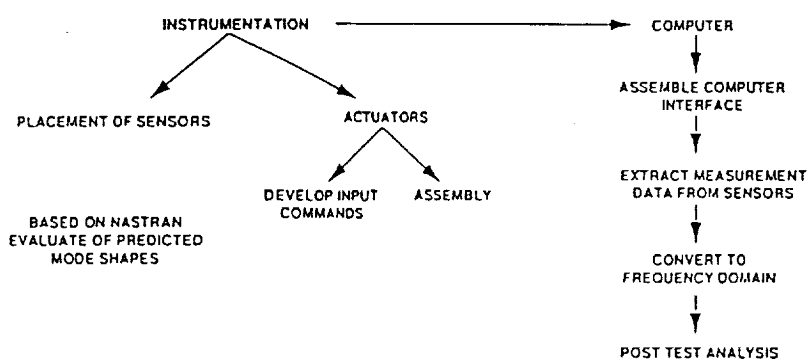

Figure 3

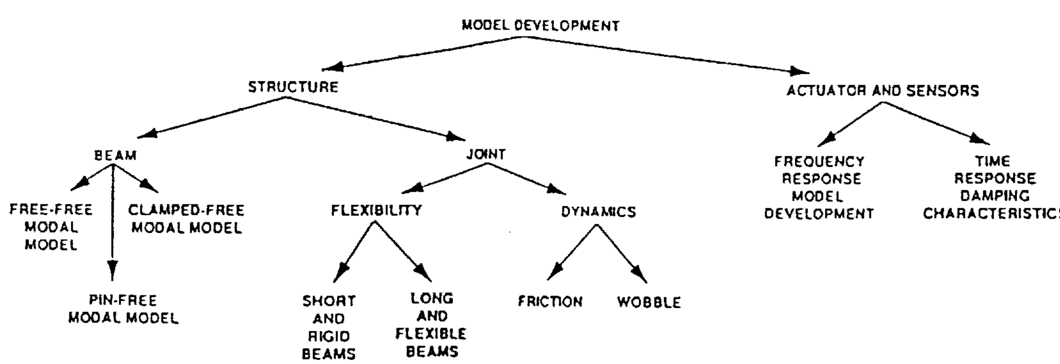

Figure 4

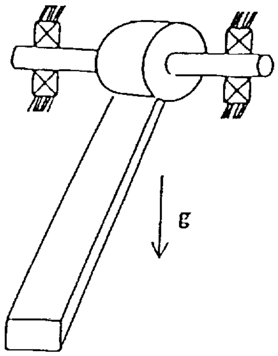

Figure 5

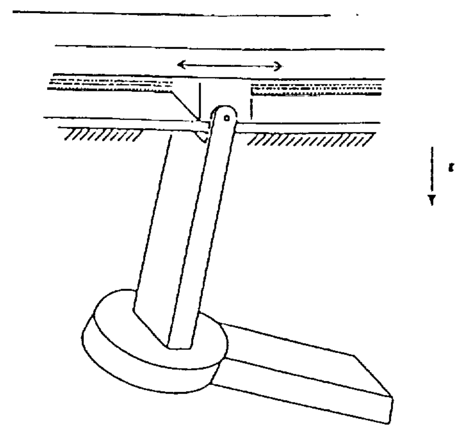

Figure 8

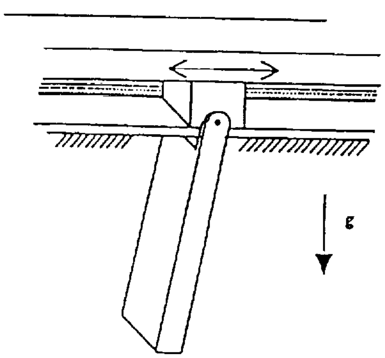

Figure 6

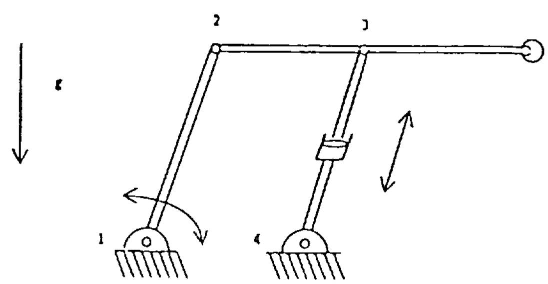

Figure 9

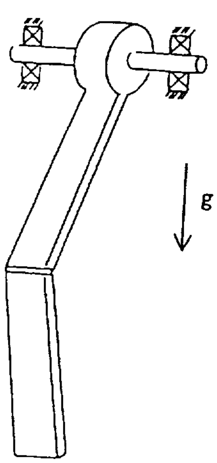

Figure 7

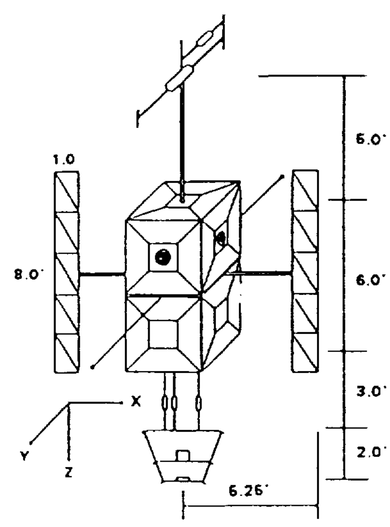

Figure 10